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# UNSTEADY SUBSONIC AERODYNAMICS FOR MANEUVERING WING/FUSELAGE/PYLON/STORE CONFIGURATION AND STORE SEPARATION INCLUDING WAKE EFFECTS

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## SUMMARY

A Computational Fluid Dynamics (CFD) technique based on a Vortex Lattice Method (VLM) is presented for treating the unsteady, low speed aerodynamics of a Wing/Fuselage/Pylon/Store (W/F/P/S) combination in an incompressible flow. The main emphasis is placed on a practical, cost-effective engineering solution of the complex problem with a reasonable computational efficiency allowing the computer code to run on small personal computers. The computational model presented in this study enables the calculation of the unsteady aerodynamic forces acting on a wing system undergoing a time dependent three dimensional motion. An unsteady, wing following and wake shedding procedure provides the transient wake shapes. Computed flow field simulations are presented for various unsteady and angle of attack conditions, involving pylon/store locations at various spanwise locations under the wing. The external store separation under the influence of the unsteady wake rollup behind the wing system is modeled by considering the full mutual interaction between the store and the W/F/P configuration. The results show that the method is capable of simulating the important features of the unsteady forces and wake development behind the W/F/P/S configuration.

## 1. INTRODUCTION

The modeling of the unsteady wake rollup behind a maneuvering Wing/Fuselage/Pylon/Store (W/F/P/S) combination and the store separation requires advanced computational techniques. A grid based approach seems to be computationally expensive requiring a grid update during the history of the flow field. On the other hand, the VLM (Vortex Lattice Method) approach is one of the most efficient tools for complex geometries as it uses only a surface grid which is relatively easy to generate (1,2,3). The VLM is basically one of many panel methods used by today's Aerodynamicist. In the present study, the VLM model of the three dimensional flow field was used to treat arbitrary maneuvers of a trapezoidal wing with and without an underwing store. A time dependent wing following and wake shedding procedure has provided the transient wake shapes and wing loading without utilizing the iterative wake relaxation procedure. A computer code, so called TRNVLM, enables the user to orchestrate the input motions of a variety of unsteady conditions.

An underwing installations affect the performance characteristics of the wing. They are frequently a source of considerable adverse aerodynamic

interference giving large increases in drag, variations in aerodynamic stability derivatives and change in flutter boundaries (4,5,6,7,8). An understanding of the wing-store interaction is central to determining the unsteady airloads, the safe store release and the sound generation characteristics.

Separation effects occur when a store is released from an aircraft and its motion is temporarily influenced by the disturbed flow between the aircraft and the store. Separation effects testing involves releasing stores from an aircraft, one at a time, under controlled test conditions. A scenario which shows negligible separation effects under one set of delivery conditions may show large separation effects at different release conditions. The total number of external stores needed for store testing reaches upto a three digits store amount for complete store characterization (4,8).

On the other hand, computer aided experiments will help the store designer to cut certain amount of possibilities before doing the full set of planned experiments. This study aims at providing a new computer aided analysis procedure that can be used to reduce the number of experiments for the store certification after the calibration and the validation of the computer code with various store testing studies.

The scope of this paper is twofold: 1) The development of a numerical procedure based on the Vortex Lattice Method (VLM) to treat time dependent aerodynamic conditions of W/F/P/S configuration which moves along a prescribed path of motion, 2) The application of a simple computational approach to study unsteady store separation from an underwing pylon. Although the basic W/F/P/S configuration to be considered in this study is simple compared to more realistic arrangements, it will provide a first step to future where more realistic geometries including boundary layer effects will be used.

## 2. NUMERICAL SIMULATION METHODS

There are various theoretical and experimental methods to study the nonlinear aerodynamic characteristics of the wing and other aircraft components. However, the complexity of the flow require approximate models with reasonable engineering accuracy. Recent advances in techniques for exact solutions of the Euler equations and the full Navier Stokes equations require expensive computation time (9,10,11,12). The grid generation procedures still require very large programming efforts. The combined fluid dynamic problem of an external store carriage/release and three dimensional wing leading/trailing

edge separations is highly complex and a challenge to the numerical predictor.

For a maneuvering aircraft, the instantaneous state of the flow field depends on the time history of the aircraft motion. Detailed solution of the complete nonlinear fluid dynamics equations (Navier Stokes Equations) along time dependent flight paths requires the computational grid to cover large wake histories. Furthermore, during the store release, the grid update procedure at new store stations need extensive programming efforts and computing time. On the other hand, the use of simplified fluid dynamic equations while retaining the three dimensional nature of the aircraft geometry and its flight path is a realistic engineering approach for the problem associated with the carriage and the release of stores from an aircraft (13,14,15).

The simulation of unsteady aerodynamics and the resulting wake dynamics due to a maneuvering aircraft is very complex and it is a very difficult task for today's Aerodynamicist. The presence of external stores complicates the overall flow field over the wing. During the complex maneuvering phases of the wing, the aerodynamic loads on the store are also modified.

In this research investigation, a computational method based on the vortex ring element representation of the body surface was used to solve three dimensional unsteady flow field equations based on a Laplace Equation formulation. This method is based on the general Vortex Lattice Method (VLM) formulation (1,2). The VLM has not been developed yet to become a full surface panel method for complex configurations. However, wide applications cited in the literature makes the method an effective and practical engineering alternative to classical panel methods (1,2,3,14). Authors have aimed at developing an engineering code based on the Vortex Lattice Method ready to be used for practical applications. The present code is named as TRNVLM (Turkey Nonlinear Vortex Lattice Method) in which the main emphasis is placed towards maneuvering solid bodies along the prescribed paths and the store separation modeling during the path of the body motion. The TRNVLM computer code is written in FORTRAN language and it is open to structural modifications. Currently it is running on a 80486 type PC computer with a minimum required 8 Mb RAM total memory.

### 3. BRIEF DESCRIPTION OF THE FLUID DYNAMICS MODEL

The following brief description is aimed at explaining the important steps of the numerical formulation. More details on the principals of the formulation can be obtained in the text book by Katz and Plotkin (14, pages 422-431). The motion history of the W/F/P/S coordinate system  $(x,y,z)$  is assumed to be known and orchestrated in an inertial frame of reference  $(X,Y,Z)$ . The relative motion of the origin of the W/F/P/S fixed frame reference is given by  $R_o(x,y,z;t)$  and the instantaneous rotation angles are given by  $\Theta_o(\phi,\theta,\psi;t)$  (See Fig.1).

It is assumed that the flow is incompressible, inviscid and irrotational over the entire flow field apart from

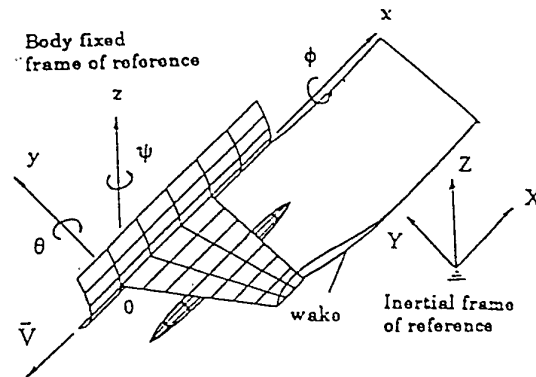


Figure 1. Research geometry and frames of references to describe the motion of the W/F/P/S configuration.

the solid boundaries and its wakes. A disturbance velocity potential  $\Phi(X,Y,Z)$  can be defined in the inertial frame and the continuity equation becomes

$$\nabla^2 \Phi = 0 \quad (1)$$

The first boundary condition requiring zero normal velocity across the body's solid boundary is

$$(\nabla \Phi + \vec{V}) \cdot \vec{n} = 0 \quad (2)$$

where  $\vec{V}$  is the kinematic velocity of the W/F/P/S surface due to the motion as viewed in the body frame of reference, and  $\vec{n}$  is the normal vector to the surface in terms of the body surface coordinates. If we let  $\vec{V}_o$  be the kinematic velocity of the  $(x,y,z)$  system's origin

and  $\vec{\Omega}$  be the rate of rotation of the body frame of reference, the boundary condition which requires zero normal velocity at each control point on the body is satisfied by the equation,

$$(\nabla \Phi - \vec{V}_o - \vec{v}_{rel} - \vec{\Omega} \times \vec{r}) \cdot \vec{n}_i = 0 \quad (3)$$

where  $\vec{r}(x,y,z)$  is the position vector in body  $(x,y,z)$  coordinates and  $\vec{v}_{rel}$  is the velocity due to an additional relative motion with respect to  $(x,y,z)$  system. This last velocity vector is needed during the application of the store separation from the wing to satisfy the boundary condition on the store surface.

The second boundary condition for Eq. (1) requires that the W/F/P/S induced disturbance will decay far from the body. Hence,

$$\lim_{r \rightarrow \infty} \nabla \Phi = 0 \quad (4)$$

For the unsteady flow, the use of the Kelvin condition supply an additional condition that can be used to determine the streamwise strengths of the vorticity shed into the wake. The overall circulation,  $\Gamma$ , around a fluid curve enclosing the body and the wake is conserved,

$$\frac{d\Gamma}{dt} = 0 \quad (\text{for any } t) \quad (5)$$

The solution of Eq. (1) with the above boundary conditions can be obtained by using Green's theorem which states that a general solution consists of a doublet and source distribution over the body surface and the wakes (14). However, as noted by Katz (2,14), for the lifting problem solution, the vortex distribution, which can be defined by doublets, is sufficient. In the present study, every surface is treated as a lifting surface and they were divided into panels. Then a vortex ring was placed on each panel (See Figure 2).

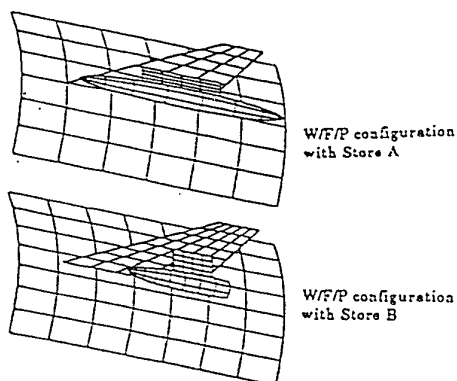


Figure 2. Example of a vortex lattice system on a W/F/P/S system

The zero thickness wing lifting surface is divided into  $N \times M$  ( $N \times M = NW$ ) vortex rings with streamwise panelling. Each vortex ring of an unknown strength,  $\Gamma_{w,j}$ , ( $j=1, NW$ ) is bound to the 1/4 of the panel chord thus satisfying the Kutta condition. Similar to the wing surface panelling, fuselage is divided into  $NN \times MM$  ( $NN \times MM = NF$ ) vortex rings with,  $\Gamma_{f,j}$ , ( $j=1, NF$ ) vortex strengths, pylon is divided into  $NNN \times MMM$  ( $NNN \times MMM = NP$ ) vortex rings with,  $\Gamma_{p,j}$ , ( $j=1, NP$ ) vortex strengths. Finally, the external store surface is divided into  $NNNN \times MMMM$  ( $NNNN \times MMMM = NS$ ) with,  $\Gamma_{s,j}$ , ( $j=1, NS$ ) vortex strengths.  $Nxxx$  and  $Mxxx$  values represent the number of panels in the spanwise and chordwise directions respectively. Two different store geometries are studied in this investigation. The W/F/P and Store A combination is used basically to study unsteady wake characteristics. On the other hand, the W/F/P and store B combination is used both in the investigation of the transient wing/store force characteristics and the store release analysis. The lattice model of the configuration with Store B consists of 261 vortex rings, with  $NW=100$ ,  $NF=64$ ,  $NP=25$  and  $NS=72$  (See Figure 2).

The complete solution of the problem in terms of the unknown bound circulation strengths,  $\Gamma_{w,j}$ ,  $\Gamma_{f,j}$ ,  $\Gamma_{p,j}$  and  $\Gamma_{s,j}$ , is carried out by satisfying Eq.3. The induced velocity,  $(\partial\Phi/\partial z)_{i,j}$ , due to W/F/P/S ring vortices, the wing trailing edge wake and the wing tip wake elements is given at each control point by (14),

$$\left(\frac{\partial\Phi}{\partial z}\right)_{i,j} = \begin{bmatrix} \Gamma_1 \\ \vdots \\ \Gamma_{NW} \\ \vdots \\ \Gamma_{NF} \\ \vdots \\ \Gamma_{NP} \\ \vdots \\ \Gamma_{NS} \end{bmatrix} = [WFPS] \begin{bmatrix} 1 \\ \vdots \\ 1 \\ \vdots \\ 1 \\ \vdots \\ 1 \\ \vdots \\ 1 \end{bmatrix} + [TEWI] \begin{bmatrix} 1 \\ \vdots \\ 1 \\ \vdots \\ 1 \\ \vdots \\ 1 \\ \vdots \\ 1 \end{bmatrix} + [TIPI] \begin{bmatrix} 1 \\ \vdots \\ 1 \\ \vdots \\ 1 \\ \vdots \\ 1 \\ \vdots \\ 1 \end{bmatrix} \quad (6)$$

The influence matrix coefficients  $[WFPS]$ ,  $[TEWI]$  and  $[TIPI]$  in this equation represent the influence of a

unit singularity distribution on a panel acting at the control point of another panel. The influence coefficient matrices are obtained by using the Biot-Savart law. If the W/F/P/S geometry is unchanging with time,  $[WFPS]$  remains constant, although  $[TEWI]$  and  $[TIPI]$  are varied due to wake evolution. In the case, where we study store separation, a relative motion between the store and the other bodies is important. Hence, the coefficients representing the influence of the store on other bodies must be updated at any moment,  $t$ . The kinematic velocity  $W_{i,j}$ , at each control point, is due to

W/F/P/S instantaneous velocities,  $\bar{V}$  and rotations,  $\bar{\Omega}$ . Then the final condition that satisfies Eq. 3 will be,

$$W_{i,j} + \left(\frac{\partial\Phi}{\partial z}\right)_{i,j} = 0 \quad (7)$$

This equation yields a set of  $n$  ( $n=NW+NF+NP+NS$ ) linear algebraic equations for  $n$  bound body vortex strengths. An indirect method, the Gauss Seidel iterative technique is used to solve the unknown intensities of the vortex ring elements.

#### Vortex Wake Modelling

The unsteady wake roll up behind a maneuvering W/F/P/S configuration is studied by properly accounting the local flow separation from the wing tip and trailing edges. The VLM approach is one of the most efficient tools among the typical and widespread singularity methods for the modeling of the unsteady wake structure. The ability of the method is well demonstrated in the literature (1,2).

A lagrangian type wake shedding procedure is used. The modeling of the wake, which is shed from the wing tip and the trailing edge, is achieved by releasing vortex ring segments at each time interval from the corresponding edges. The vortex ring segments released at each time step,  $\Delta t$ , build the continuous wake structure behind the wing. The instantaneous wake deformation is simulated by calculating the velocities at each ring corner point. Then, based on an explicit single step Euler scheme, the vortex rings are moved. A very simple vortex core model (core radius equals to  $0.001 \cdot CR$ ) is used for the wake rollup procedure.

The modeling of the flow separation from the bluff store geometry was neglected and left for the future study. However, the kinematic velocity of the W/F/P/S system defines the direction of the vortex filaments of the F/P/S trailing edge horseshoe vortices, representing the vorticity field shed from the fuselage, pylon and the store trailing edges.

#### Unsteady Aerodynamic Loads

The calculation of aerodynamic loads on the store during carriage and release requires complicated aerodynamic strategies. In the present investigation this task involves the following sources of effects; a) unsteady interference of the wing/store system, b) the disturbance on the store caused by the unsteady wake rollup, c) unsteady effects including store and wing rotations during release and maneuvering. To evaluate these interference effects, two computation tasks were carried out simultaneously, 1) the continuous mutual interference evaluated by unsteady aerodynamics including wakes, 2) the resulting store motion by flight mechanics.

After the solution of the vortex circulation strengths, the unsteady surface pressures are computed by using the Bernoulli's equation. The pressure coefficients are given by the following relation (14),

$$c_p = \frac{p - p_{ref}}{\frac{1}{2} \rho v_{ref}^2} = -\frac{(\nabla \Phi)^2}{v_{ref}^2} + \frac{2}{v_{ref}^2} [\bar{V} + \bar{v}_{ref} + \bar{\Omega} \times \bar{r}] \cdot \nabla \Phi - \frac{2}{v_{ref}^2} \frac{\partial \Phi}{\partial t} \quad (8)$$

where  $p_{ref}$  is the far field pressure and  $v_{ref}$  is the kinematic velocity defined as

$$\bar{v}_{ref} = \bar{V} + \bar{\Omega} \times \bar{r} + \bar{v}_{ref} \quad (9)$$

The contribution of a vortex ring element with an area of  $\Delta A_k$  to the aerodynamic load,  $\Delta \bar{F}_k$  is given by

$$\Delta \bar{F}_k = -c_{p_k} \left( \frac{1}{2} \rho v_{ref}^2 \right) \Delta A_k \bar{n}_k \quad (10)$$

The resulting three dimensional forces and moment coefficients are obtained by integrating each panel normal force,  $\Delta \bar{F}_k$ , along the body surface (14).

### Store Separation Analysis

The store separation prediction techniques in use throughout NATO countries have already been discussed in the literature (4,6,8). These techniques may be discussed under three main categories: theoretical, empirical and analogy. The present study uses the theoretical approach. The theoretical store separation predictions utilize flow equations which can be either coupled or uncoupled to the equations of the store motion. By coupling the flow equations to the equations of motion, we can solve for the new altitude of the store at a specified interval of time and then use this new aircraft/store physical relationship to calculate a new flow field. In the present study, both the equations of flow and the equations of the motion are solved together.

Meto and Kaykayoglu (16) have previously investigated the separation characteristics of a store after release from an aircraft by using a flow grid method combined with a classical panel method. The similar approach was also applied by Von der Broek (17). The computer code developed by Meto and Kaykayoglu applies panel singularity distribution over the surface of the F-4 type aircraft. The isolated store, after separation from the aircraft, moves through the nonuniform flow field consisting of the free stream plus the perturbation flow field created by the aircraft. The nonuniform flow field is defined at the mesh points of a three dimensional orthogonal grid covering the separation region of interest. Hence, the presence of the store has no direct influence on the perturbation flow field. The computer code numerically integrates the six degree of freedom (6 DOF) equations of the store motion for a specified small time interval,  $\Delta t$ , to arrive at a new store position in the flow grid system. Figure 3 shows two store separation scenarios studied so as to understand the effect of store spanwise location on the store trajectory characteristics.

The separation prediction of an external store from the W/F/P system requires the evaluation of unsteady aerodynamic forces and moments on the store. These parameters depend upon the nonuniform flowfield around the W/F/P and the store motion itself. Deslandes (18) have outlined the concepts about the evaluation of aerodynamic loads on the external stores which is related to the aerodynamic coupling of four

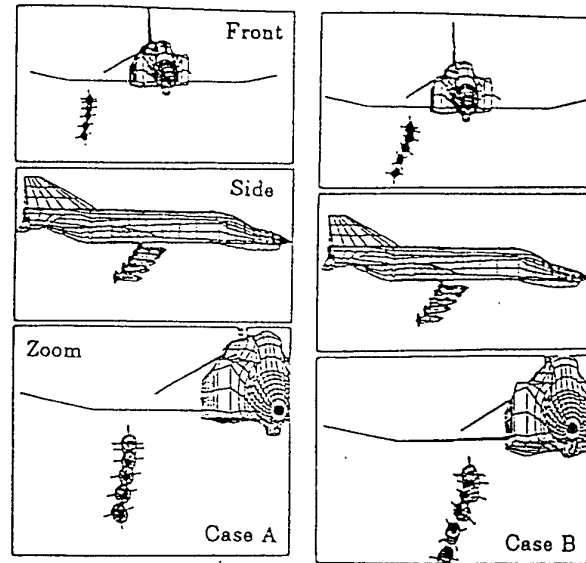


Figure 3. Store separation analyses by using a combined panel method/flow grid technique (16).

main effects. Due to the first order effects present in the method used by Meto and Kaykayoglu, authors of the present paper has preferred to use a new approach which will be more realistic and accurate for the prediction of the store trajectory. This new approach enables continuous interaction between the W/F/P and the store. In the present study, we consider 1st, 2nd and some of the higher order effects to evaluate the unsteady aerodynamic loads on the external store as described by Deslandes. First order effects, which stands for the steady interference of the W/F/P and the airflow around the store, is valid during the advancement of the store over a time step which corresponds to the shedding of one row of wake vortices from the wing's trailing edge. Second order effects, which stands for the relative motion of the store and the W/F/P including instantaneous rotations are included fully in the formulation. Higher order effects due to wake rollup during unsteady maneuvers of the W/F/P combination are also taken into account.

Aerodynamic forces and moments on the store are computed and then supplied to the 6 DOF equations of motion. The force and moment data are combined with the weight, moments of inertia and center of gravity information of the store. Then the equations of motion are solved by using a second order Runge Kutta scheme to predict the store's next position relative to W/F/P system. The time interval for shedding a vortex ring into the wake is divided into 20 equal time increments and  $\Delta t / 20$  is used as a time step in the Runge Kutta integration scheme. The force and moment characteristics are updated at each time step. A new store position is then used in the next time step when a new row of vortex rings are released from the wing tip and trailing edges. The computer simulation procedure is very much similar to the experimental technique so called Captive Trajectory System (CTS) (4).

In the simulation procedures, aerodynamic force and moment coefficients have to be scaled to the actual flight conditions. The accelerations of the store model will be similar to the full scale flight conditions if the total forces and moments, mass, center of gravity and

moments of inertia are properly scaled to flight conditions (4). Vortex Lattice Method based computer codes are capable of simulating low speed, incompressible fluid flows if no transformation is used to introduce compressibility effects. Hence we can assume that the simulation is reasonably valid upto Mach number 0.3 ( $Ma=0.3$ ). In the present investigation, we have used linear geometric and velocity scaling for the research configuration assuming  $Ma=0.1$ . Although the present store trajectory program provides reasonable store release scenario, the sensitivity of the method to many different variables should be further studied.

#### 4. RESULTS AND DISCUSSION

Figure 4 shows the research configuration featuring W/F/P/S setup in details. The research wing has an Aspect Ratio,  $AR=3$  and zero thickness. The geometry of several classes of wing systems can be defined by parameters like sweep, camber and twist by the geometry module of the computer code prepared. Present investigation considers a trapezoidal wing with the relevant dimensions of  $CR/CT=3.28$ ,  $S/CR=2$  and  $\Lambda = 35^\circ$ . The W/F/P/S configuration is considered to be symmetric with respect to the plane shown in Fig. 4.

As mentioned earlier, two store geometries were studied in our investigation. The store A has a symmetric ellipsoidal geometry and the store B has an ellipsoidal geometry with a tapered trailing edge. The location of the store installation under the wing is chosen with respect to the geometric center of the store measured from the origin of the body reference axis. The Store Aspect Ratio, SAR, Store Spanwise Location, SSL/CR, Store Transverse Location, STL/CR and Store Chordwise Location, SCL/CR are the main parameters used in this investigation. The pylon has a rectangular geometry. The geometry of the pylon can be defined by parameters like used in the wing system. And finally, the wing-fuselage interaction problem is handled similar to the work of Atta and Nayfeh [ 19 ].

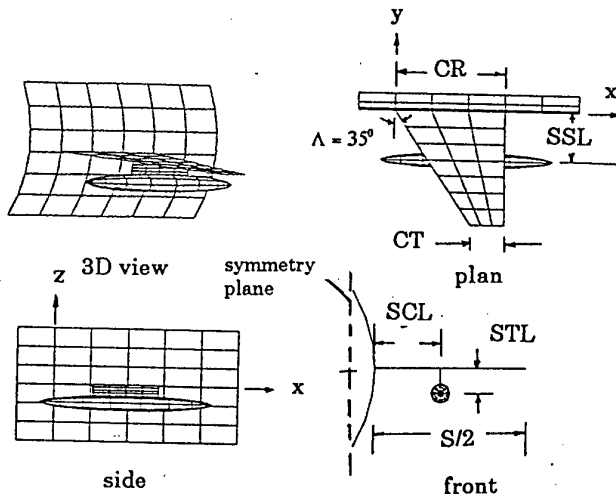


Figure 4. Geometry of the W/F/P/S combination and important parameters.

##### Validation of the Computer Code, TRNVLM

As means of establishing the credibility and the engineering accuracy of the computer code, TRNVLM, some basic applications of the steady and unsteady aerodynamics will be presented first.

Computer experiments have been performed to predict the lift coefficient value as a function of angle of incidence for various rectangular wings having different Aspect Ratio,  $AR$ . The variation of the lift coefficient slope with the Aspect Ratio is presented in Figure 5a. The computed results agree well with the theoretical values obtained by Graham (20). The curves shown in Figure 5b are the predictions of the transverse loads on a rectangular wing having an  $AR=1$ . In this Figure, the experimental results of Lamar (21) and the computational results of Fang and Luo (22) are also shown. The computational results of Fang and Luo are based on a Vortex Lattice type modeling,

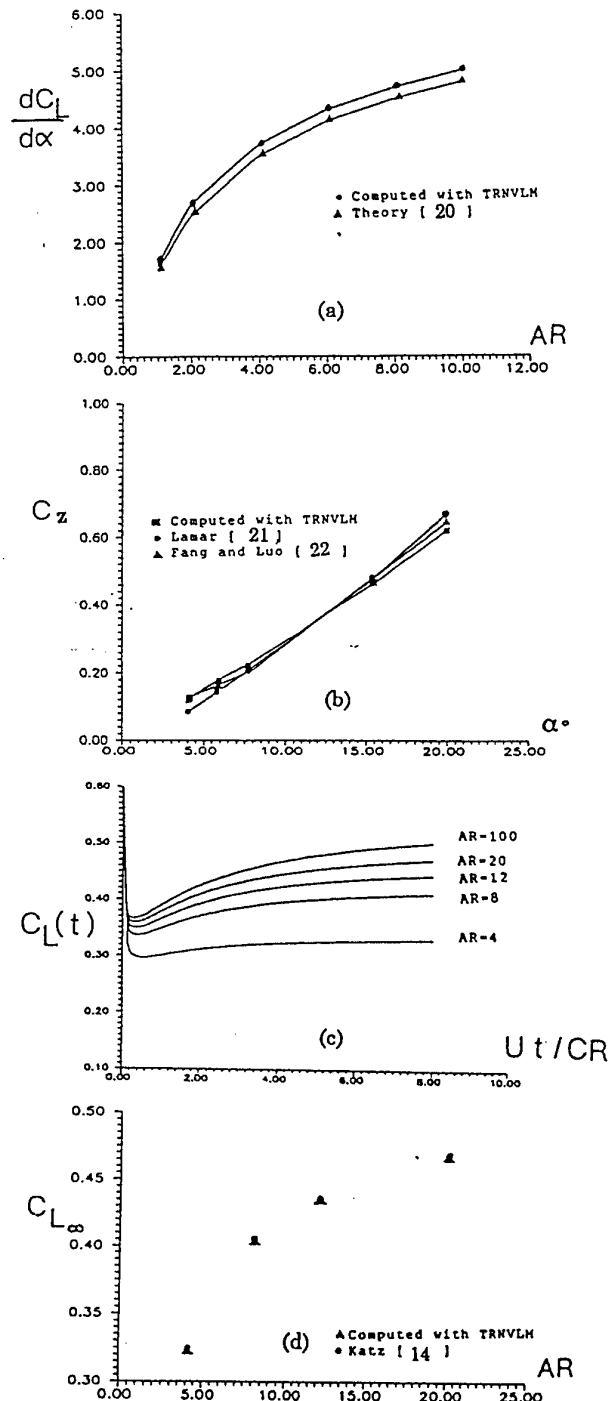


Figure 5. Validation of the computer code, TRNVLM.

too. The predictions with TRNVLM computer code are very near to both results. The transient lift coefficient variation with time for various aspect ratio rectangular wings which are suddenly set into forward flight is depicted in Figure 5c. A steady state configuration of the near wake is reached for a dimensionless time,  $T$ , approximately equal to 6. A comparison of the steady state lift coefficient predictions between the present computer code and the computational code supplied by Katz (14) is shown in Figure 5d. The agreement between two codes are remarkable.

The present computer code, TRNVLM is capable of predicting the unsteady wing loading during maneuvering flight along a three-dimensional prescribed path. The computer code, in its current state, simulates diving, climbing, pitching, heaving and rolling motions or combination of these motions where predictions by experiments and other computational techniques are limited. Furthermore, the unsteady aerodynamic problem associated with the release of a store at any instant of the maneuver can be modeled by the computer code. The examples presented in the next section serves mainly to understand the unsteady nature of both the flow field and the aerodynamic loading during the store carriage and release.

#### Wake Development: Effect of angle of attack

The near wake of an aircraft has major effects on the aircraft's aerodynamic characteristics, such as tail plane loads, wake induced turbulence on the approaching aircraft, wing pressures and store trajectory paths after the release. For this reason, it is essential that a computational code can model wakes accurately.

Figure 6 shows an overall plan view of the instantaneous structures of the trailing edge wakes for different angle of attacks. The shed vortex rings deform continuously under the influence of W/F/P/S configuration. The continuous spill of the flow from the lower surface of the wing combines with the upper surface flow and then forms the classical wing tip vortices at high angle of incidences. The new flow field boundary conditions imposed by the store modifies the near wake structures by creating an additional longitudinal vorticity at high angle of incidence. The clockwise rotating wing tip vortex (viewed from the rear) is augmented at higher angle of incidences. Along the wing/fuselage junction the wake is attached to the fuselage surface until it leaves the body. The similar vortex roll-up but in the counterclockwise direction takes place along the wing-fuselage junction as the wake develops in the streamwise direction. At  $\alpha = 20^\circ$  there exists an additional secondary vortex rollup in the clockwise direction starting at about three root chord distances from the trailing edge of the wing. Such kind of a wake character also appears for the negative angle of incidence. In negative angles of attack, the secondary vortex, rotating counter clockwise forms early at about two and a half root chord distance (viewed from the rear) and then spirals into a large vortex core. Similar type of vortex formations were also observed behind a wing/ trailing edge flap combination [ 18 ].

Figures 7 through 10 show the main features of the trailing edge near wake development in details as a function of angle of attack at a nondimensional time,

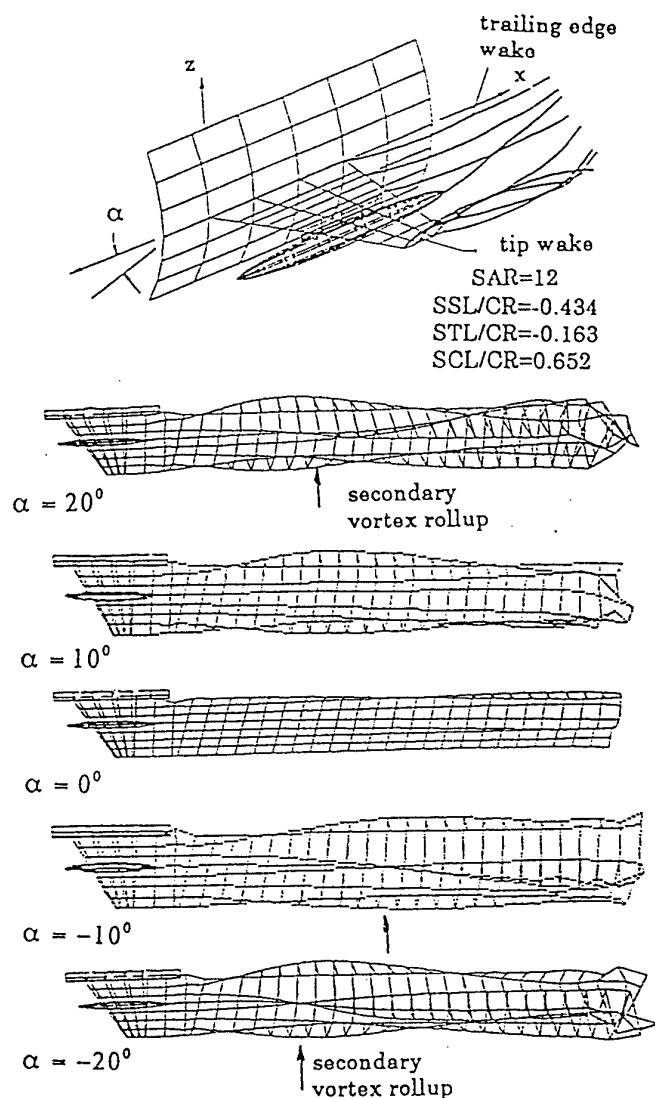


Figure 6. Computed shapes of separated trailing edge wake structures behind the research configuration: effect of angle of attack.

$T = U_\infty t / CR = 8.3$ . The pictures are presented at various view angles. Figure 7 shows the case for  $\alpha = 0^\circ$  of incidence. The instantaneous wake structure is represented with the deformed shapes of the shed vortex rings. The side view of the complete wake development is shown in Fig. 7a. The transient wake development near the wing/fuselage juncture shows both a twist and also a light roll-up in the counterclockwise direction (See Figure 7b). The roll up of the trailing edge wake is viewed from the rear parallel to the wing's trailing edge in Fig. 7c. The wake is deflected down by forming a bowl shape under the continuous influence of the store. The wake exhibits a strong antisymmetry thus more likely to cause an antisymmetric and downward forces on the wing.

Figures 8a-c present the wake structure for an angle of attack (climb mode) value,  $\alpha = 10^\circ$ . Figure 8a shows the side view of the streamwise vortex rings separating from the trailing edge. The distortion of the near wake due to the presence of the external store is shown from different view angle in Fig. 8b-c. There is no indication of a secondary roll up in the wake region. At a higher

positive angle of attack value,  $\alpha = 20^\circ$ , the lateral size of the wake, hence the extend of the rotational region, increases ( see Figures 9a-c ). The secondary rollup of the wake sheet with the influence of store complicates the wake structure. This new vortex mechanism controls the final wake shape by modifying the classical wake formation.

The direction of the wake deflection is downward for the negative values of angle of incidence ( dive mode ). Figure 10 shows the instantaneous wake structure from different view points. The wake sheet deflects slightly upward near the trailing edge of the wing and then deflects downwards. The upward deflected wake shape with the presence of a secondary vortex, rotating in the counterclockwise direction between the wing tip and wing/fuselage junction, is the important character of the transient wing motion during the forward dive motion.

Recently, Richason, Katz and Ashby (23) have investigated the interaction between two airplanes, large and small, flying along different paths by the use of an unsteady panel method. It was shown that the transient interaction between two airplanes causes significant changes on the time dependent forces. This is due to the unsteady nature of the bound wing vortices and the trailing edge wake developing behind them. The downwash induced by a large aircraft's wake modifies the aerodynamic loading on the smaller aircraft underneath. Hence, the interaction between two aircrafts are very much functions of the unsteady wake shapes. We believe that, the wake-aircraft interaction will be quite different under the continuous effect of an external store system on the developing trailing edge wake structure.

#### Unsteady Wing and External Store Loading

The transient development of the force coefficients for the wing and store geometries that were suddenly put into forward climbing motion is reported in this section. In the first part of the presentation, the wing lift coefficient variation due to the forward climb motion will be discussed. This discussion will be followed by presentation of the 3-D transient force development on the external store.

The transient lift coefficient variation for the wing suddenly set into a climb motion without an external store is presented in Figure 11. The final wake structure behind the W/F/P configuration is also presented by using streamwise vortex filaments as a function of angle of attack. During the early phases of the motion, the rate of change of the unsteady force coefficient is very large. The lift coefficient reaches its steady state value under the transient effect of the starting wing vortex and also due to the change in downwash velocities induced by the wake. The initial lift build up continues almost three root chord distance of motion for all the cases investigated in Figure 11.

Figure 12 depicts the transient lift coefficient development for the wing with an external store that is suddenly set into climb motion. In these cases, the length of the transient lift build up is a function of angle of attack. A relatively short length of transient lift development is obtained at  $\alpha = 10^\circ$ . The steady state lift value is reached after two root chord distance. The initial time length for the lift build up increases with

the angle of attack. It is clear that the presence of the store modifies the initial lift variation by causing additional perturbations. The presence of the store dramatically reduces the lift values. This is primarily due to the changing wake characteristics as shown in the Figures. Of course, the change in the strengths of the wing bound vortices due to the store presence is the other major source of reason.

The cross comparison of the steady state wing lift coefficient values with and without an underwing store are presented in Figure 13 as a function of angle of attack. The variation is almost linear for the range 0 to 20 degrees. There is a negative lift value at 0 degree of incidence due to the presence of an external store. The lift coefficient values are reduced by more than 50% due to the wing-store interaction.

Understanding of the transient force development on the external store is extremely important since the characteristic values set the initial conditions for store separation. For this reason the instantaneous pressure distribution over the store surface is integrated over the subsurfaces and the normal force values are determined. By resolving the normal force components in three directions, the transient force component history is obtained (See Figure 14). Figure 15 shows the variation of the external store force coefficient in the streamwise direction as a function of angle of attack. The x-component of the store force values are found to be all positive. The streamwise x-force component decreases as the climb angle increases. The transient nature of the force variation increases with the angle of attack value. The z-directional force values are positive and reach maximum values at higher angles of attack (See Figure 15b). Figures 16a-c presents the transient moment coefficients of the external store during forward climb motion. Although steady state levels are reached in a relatively short time for the  $M_x$  and  $M_y$  components,  $M_z$  coefficient needs longer times to reach a steady state level.

Our calculations show that the transient force build-up on the store is different than the wing's transient lift development. Since, we assume that there is no wake shedding from the store geometry, the perturbations coming from both the neighboring bodies and the developing wing wake modify the transient force and moment history.

#### External Store Separation

The store separation analysis consisted of calculating the aerodynamic forces and moments on the store in several locations in the vicinity of the maneuvering W/F/P configuration. The authors solve for the new altitude of the store at a specified interval of time in the store trajectory and then uses this new W/F/P/S physical relationship to calculate a new flow field. The interaction aerodynamics is updated and the process is repeated for a complete store trajectory by using the new flow field.

Figure 17 shows the transient wing normal force variation as a function of initial store position during a complete store separation scenario. The store initial position data are given in the Figure. The prescribed path of the W/F/P/S system is set to a dive mode with an angle of attack value -20 degrees. It is planned to release the store at a nondimensional time,  $T=2.6$ . The



whole configuration is assumed to continue its motion along the preset path after the store separation. As the W/F/P/S configuration set into a dive motion, a negative normal force starts to build up on the wing. Almost 99% of the steady state force level is reached by  $T=2.6$ . At this instant of time, store is released from the pylon. After the store separation, the negative force coefficient value drops sharply. Then it reaches a constant value near  $T=4.6$ . The separation effect is reflected on the transient force coefficient variation for 2 nondimensional time units. A slight change in the relative store position results in a dramatic force variations (Observe the change in the force values for the initial store position #2). In the figure, we also show the steady state force coefficient levels. These levels indicate the steady state values corresponding to the W/F/P/S configuration with no store separation. The store which is located closer to the wing tip will result in a relatively low steady state force level on the wing. The force coefficient reaches an asymptotic level after the store separation. Although it was not shown on the Figure, two asymptotic values which corresponding to two different initial store positions will go to the same limit value as the W/F/P motion continues. Figure 18a shows the separation scenario for the store released from position #1. The store trajectory path is shown at four selected instants of time. The streamwise vortex filaments are also presented in the pictures. Figure 18b shows the plan view of the position of the store at  $t = 2\Delta t^*$ . The store pitches and also rotates around the z axis along its time dependent trajectory.

Figure 19 shows the transient normal force variation as function of initial store position during a complete store separation analysis for the climb mode. The planning of the store release scenario is similar to the case described in Figure 17. After the store separation, the transient force coefficient shows a big peak under the influence of the changes in velocity potential value. A recovery takes place in a short time duration and the force coefficient attain a fairly constant value. Figure 20a-b shows the instantaneous locations of the store after a release from the pylon. Figure 20a shows the store positions at four instants of time. The store travels a relatively long vertical distance compared to the case discussed in Figure 18. Furthermore, the rotations around the store mass center is augmented. Figure 20b shows the store position at  $t = 2\Delta t^*$ . The store mass center moves laterally towards the fuselage as opposed to the case observed in the Figure 18.

Figure 21 shows the transient lift coefficient variation for a W/F/P/S motion with 0(zero) angle of incidence. W/F/P/S configuration which is set into a forward sudden motion experiences negative force value under the influence of the transient wake rollup behind the wing. As soon as the store is released from the pylon ( $T=2.6$ ), the force coefficient starts to level near a zero value. Hence, after the store separation, the clean wing enables the zero lift condition as expected. Figures 22a-d show the different aspects of the store separation. Figure 22a shows the instantaneous side view of the wake structure prior to store separation. The wake sheet is deflected downwards causing a negative loading on the wing. Figure 22b shows the final wake shape well after the store separation. Figure 22d shows a perspective view of the wake. Finally in Figure 22c, the instantaneous store positions are shown at selected times.

#### Roll and Pitch Motions During Steady Flight

Figure 23a shows the wake oscillation patterns behind the W/F/P/S configuration undergoing a roll motion at zero angle of incidence. The roll amplitude is 10 degrees and the whole configuration sinusoidally rolls with respect to x axis. The oscillation reduced frequency is  $k = 2\pi fCR / 2U_\infty = 0.95$ . The sinusoidal roll motion of the system is reflected in the wake structure. The rollup of the tip vortex sheet disappears and wake vorticity field forms crests and troughs. The wavy nature of the wake continues with a growing nature.

One of the simplest but yet an important maneuver is the oscillatory pitch motion of the system. The W/F/P/S configuration is put into a pitch mode with respect to wing apex with the same oscillation parameters chosen for the roll analysis. The final wake structure is shown in Figure 23b.

Finally, the nature of the transient force coefficient during roll motion combined with/without a store separation scenario is shown in Figure 24. The motion characteristics are as follows: oscillation reduced frequency,  $k = 2\pi fCR / 2U_\infty = 1.08$ , the roll angle,  $\phi = 2^\circ$ , and the angle of attack,  $\alpha = 20^\circ$  (dive mode). The transient force coefficient oscillates with the same frequency of the roll motion. The store separation at  $T=2.6$  slightly modifies the force values as opposed to drastic changes observed in Figures 17 and 19

#### 5. CONCLUDING REMARKS

The topic of airframe/store compatibility is of major importance to both the aircraft and store designers. The aerodynamics problem associated with the store carriage/release are very complex. In this paper, we have aimed at presenting the capability of a computer code, TRNVLM, for the simulation of this complex problem. The computer code offers a first look at details of the unsteady flow field due to store carriage/release that normally are not easy to obtain by experimental test techniques.

The Vortex Lattice Model enabled the calculation of the transient wing lift characteristics with and without an underwing store. Only a single store position is studied to reveal the transient nature of the aerodynamic forces and moments for the forward climb motion. The continuation of this work should include the investigation of other store positions.

The application of the VLM can be very useful in the study of store separation characteristics as long as the limitations of the methodology are kept in mind. Sample cases presented in this paper show that the post history of the wing transient forces after store separation is critical and should be studied in details.

Presently, the authors are working on the program to build a more reliable and user friendly source code for the aerodynamic solution of the store separation problem.

#### ACKNOWLEDGEMENT

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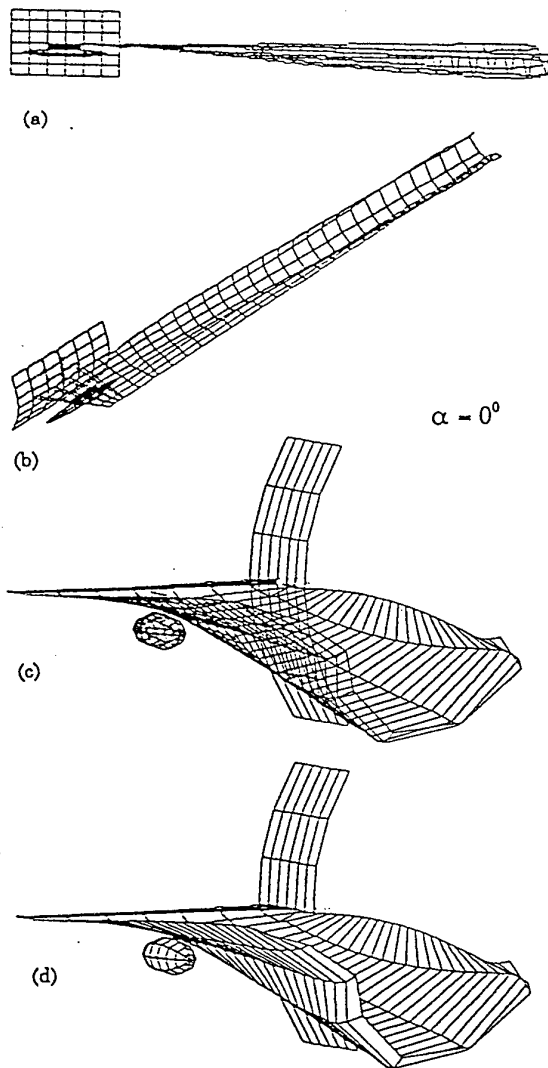


Figure 7. Computed shape of a wake structure behind the W/F/P/S configuration for  $\alpha = 0^\circ$ ; a) Side view of the wake rollup. b) Perspective view of the wake evolution. c) Rear view of the wake with wire diagrams showing the vortex lattice structure. d) Rear view of the wake with hidden vortex surfaces.

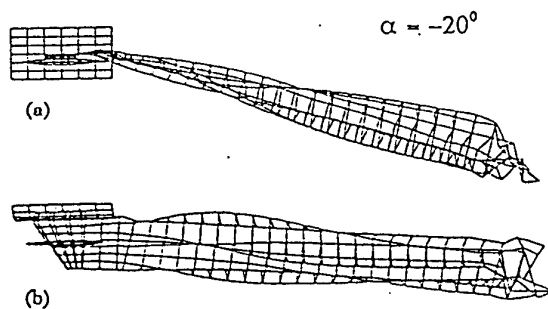


Figure 10. Computed shape of a wake structure behind the W/F/P/S configuration for  $\alpha = -20^\circ$ ; a) Side view of the wake rollup. b) Plan view of the wake evolution.

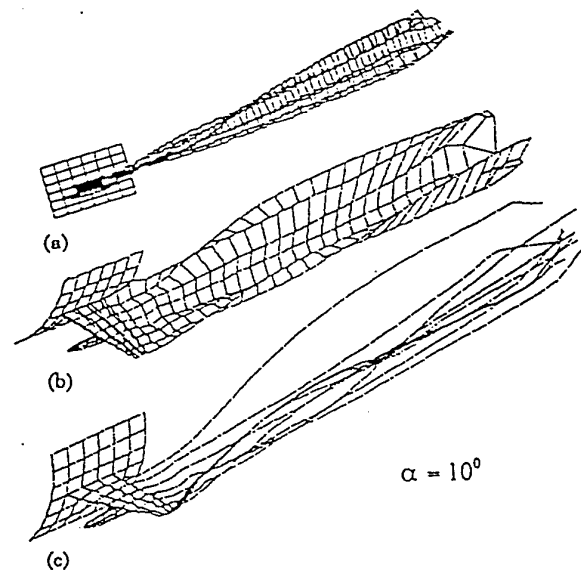


Figure 8. Computed shape of a wake structure behind the W/F/P/S configuration for  $\alpha = 10^\circ$ ; a) Side view of the near wake and deformation of the wake structure. b) Perspective details of the near wake with hidden vortex surfaces. c) Representation of the wake with streamwise vortex filaments.

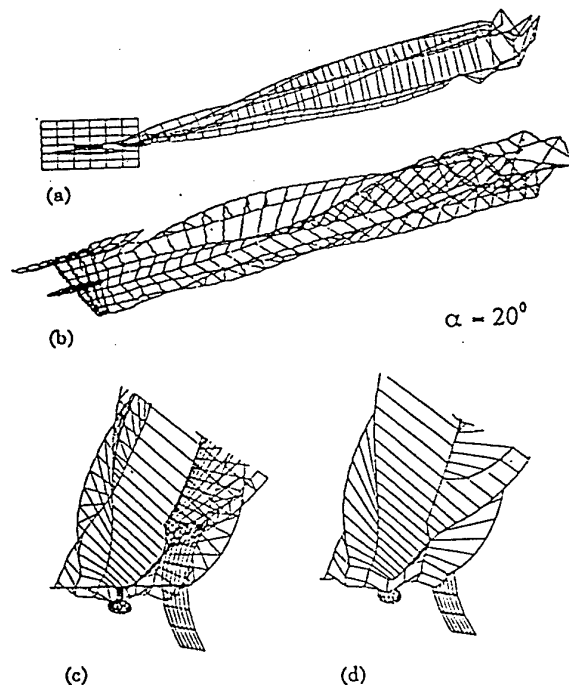


Figure 9. Computed shape of a wake structure behind the W/F/P/S configuration for  $\alpha = 20^\circ$ ; a) Side view of the wake rollup. b) Perspective view of the vortex wake evolution and the formation of the secondary vortex with the influence of the external store. c), d) Details of the near wake structure.

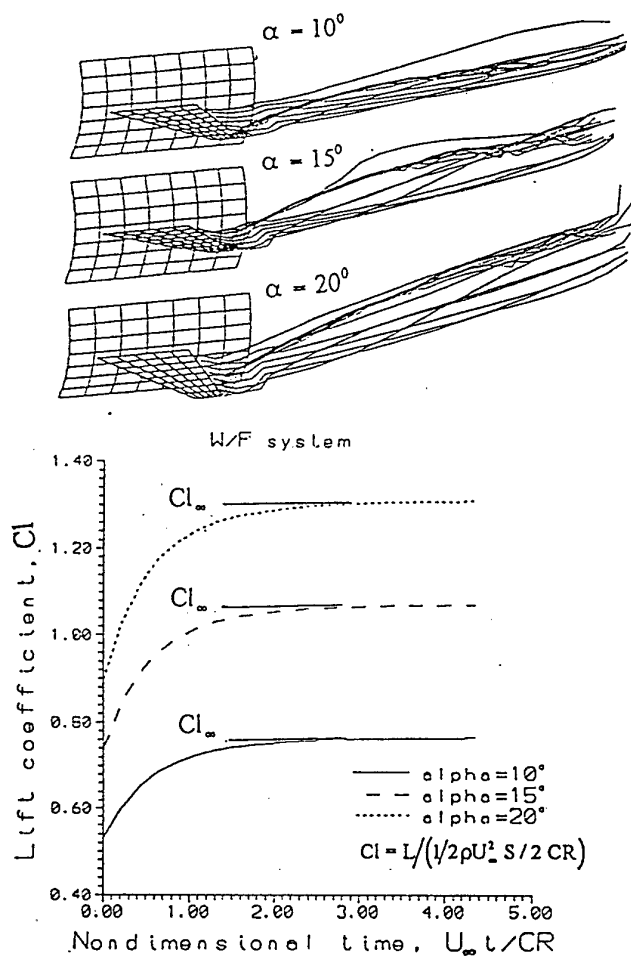


Figure 11. The transient lift coefficient of the wing after W/F configuration was suddenly set into a constant speed forward climb motion.

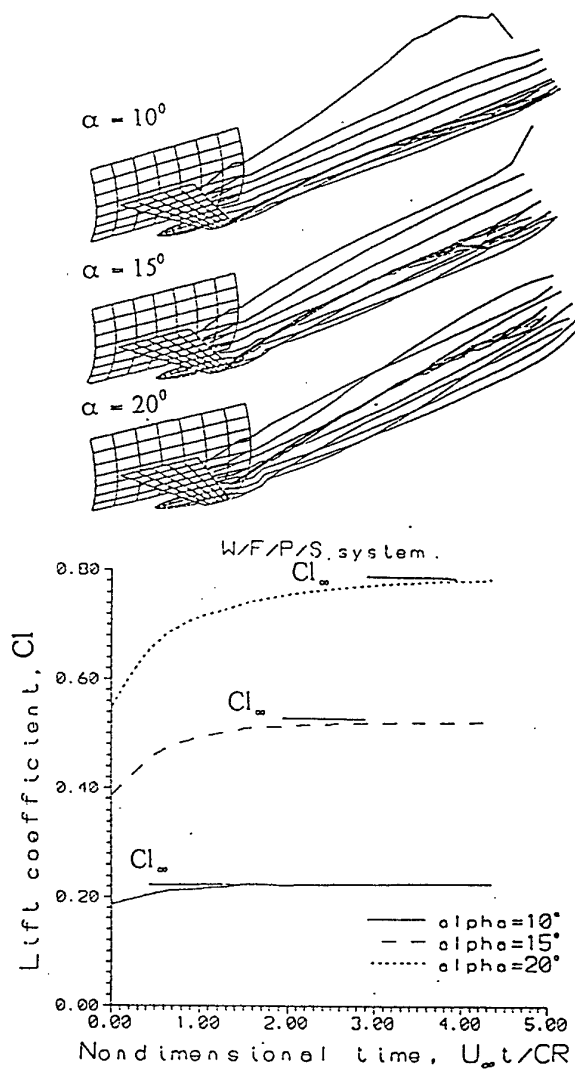


Figure 12. The transient lift coefficient of the wing after W/F/P/S configuration was suddenly set into a constant speed forward climb motion.

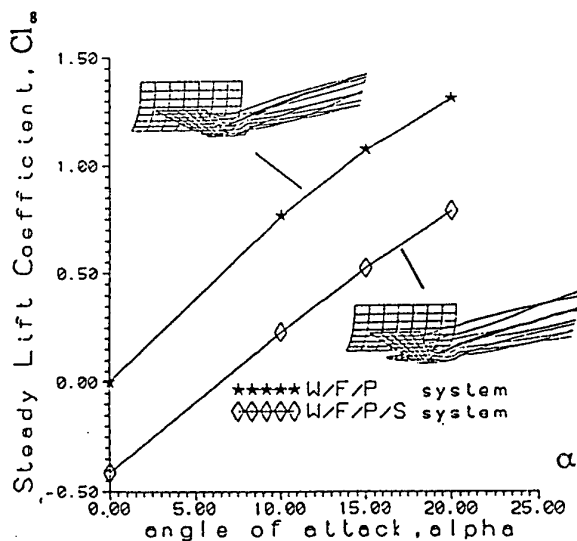


Figure 13. Effect of an external store on the steady state wing lift coefficient variation as a function of angle of attack.

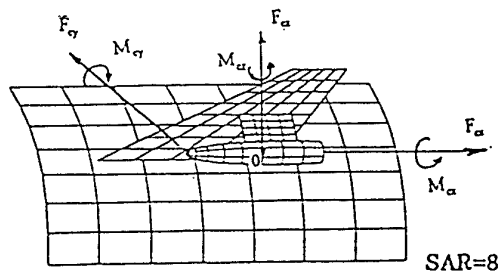


Figure 14. Underwing Store B geometry: force and moment components.

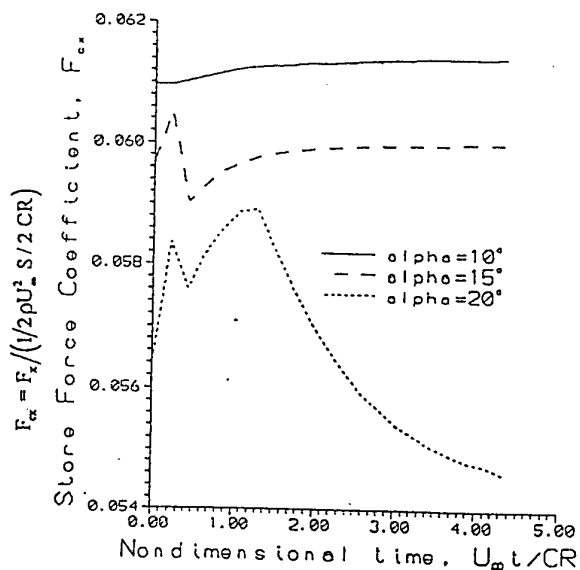


Figure 15a. The transient force coefficient,  $F_{\alpha}$ , of the store after W/F/P/S configuration was suddenly set into a constant speed forward climb motion.

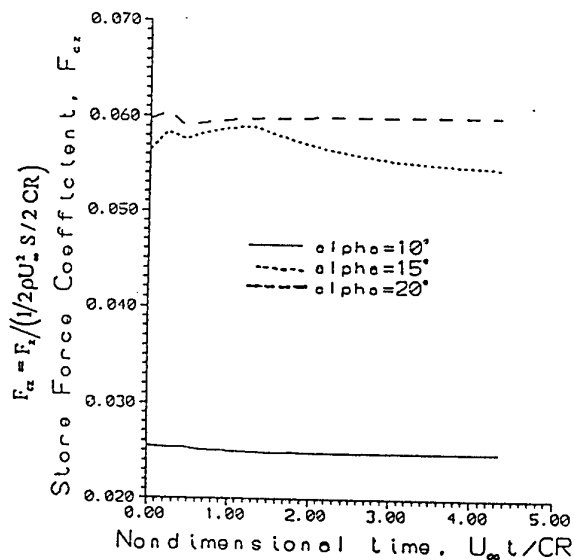


Figure 15b. The transient force coefficient,  $F_{\alpha}$ , of the store after W/F/P/S configuration was suddenly set into a constant speed forward climb motion.

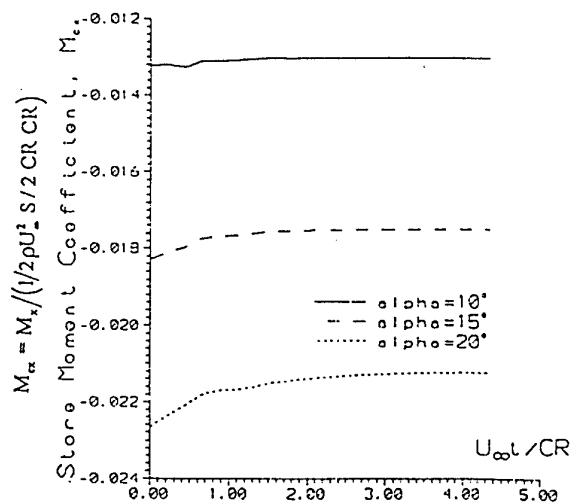


Figure 16a. The transient moment coefficient,  $M_{\alpha}$ , of the store after W/F/P/S configuration was suddenly set into a constant speed forward climb motion.

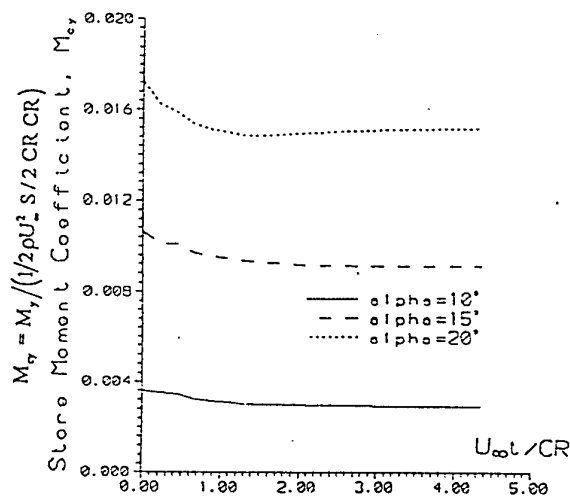


Figure 16b. The transient moment coefficient,  $M_{\alpha}$ , of the store after W/F/P/S configuration was suddenly set into a constant speed forward climb motion.

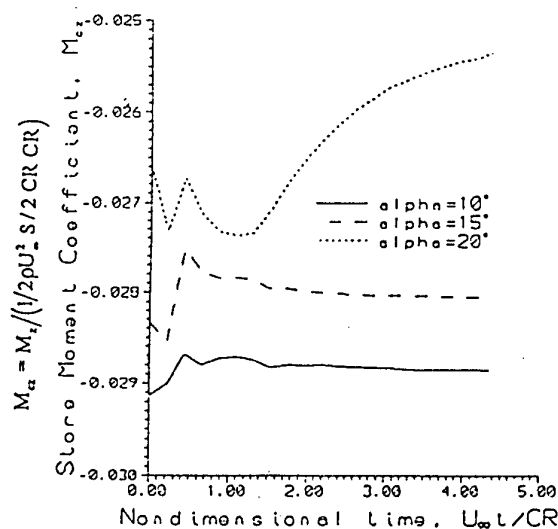


Figure 16c. The transient moment coefficient,  $M_{\alpha}$ , of the store after W/F/P/S was suddenly set into a constant speed forward climb motion.

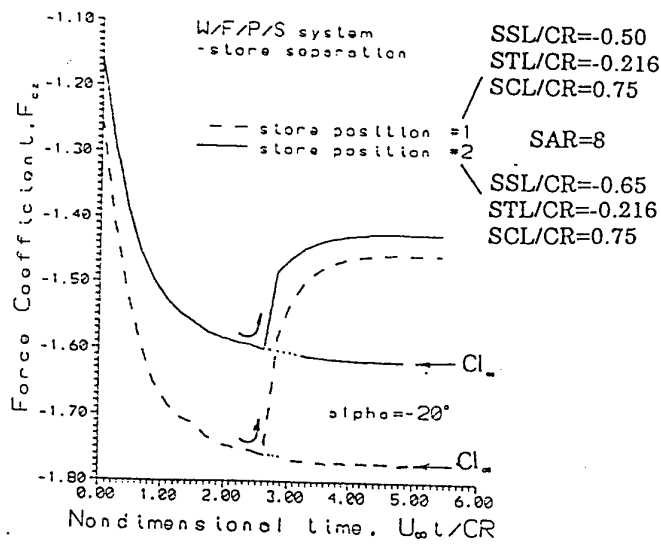


Figure 17. The transient force coefficient,  $F_{\alpha}$ , of the wing before and after the store separation during a constant forward dive motion: Effect of store position.

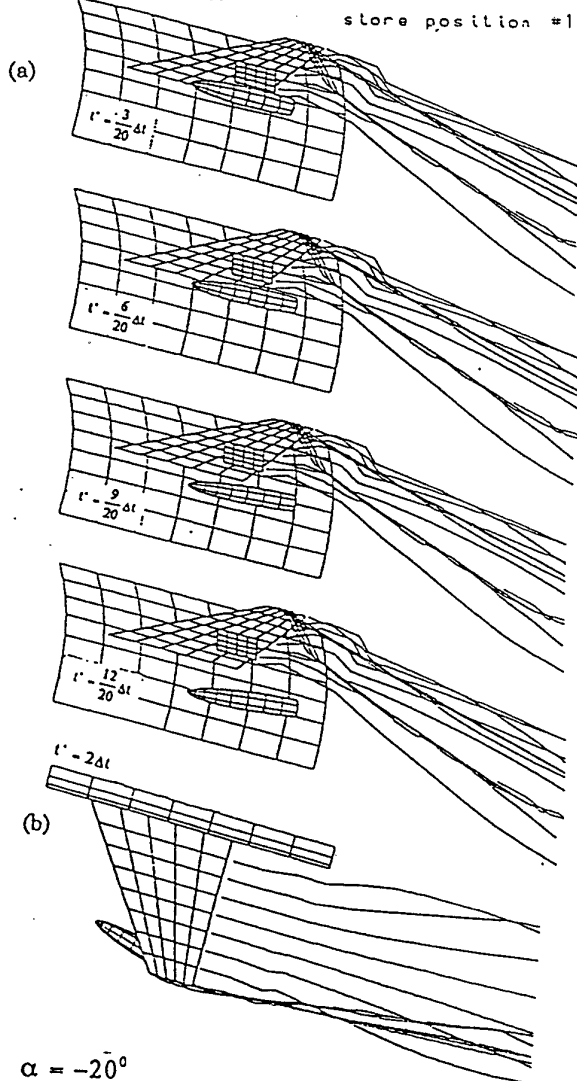


Figure 18. a) Instantaneous store positions at selected times. b) Plan view of the store position at  $t^* = 2 \Delta t$ .

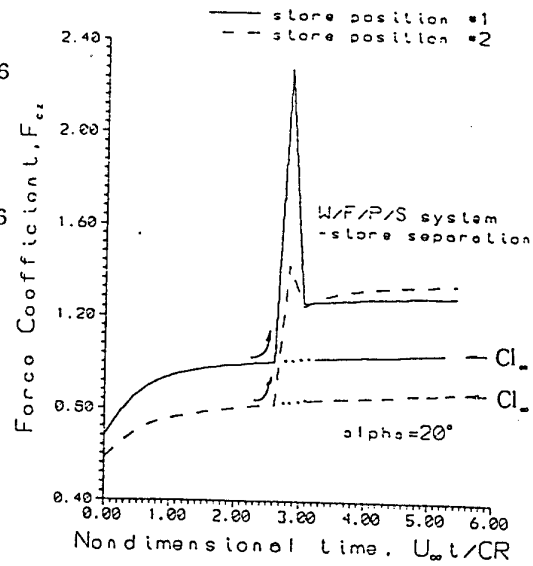


Figure 19. The transient force coefficient,  $F_{\alpha}$ , of the wing before and after the store separation during a constant forward climb motion: Effect of store position.

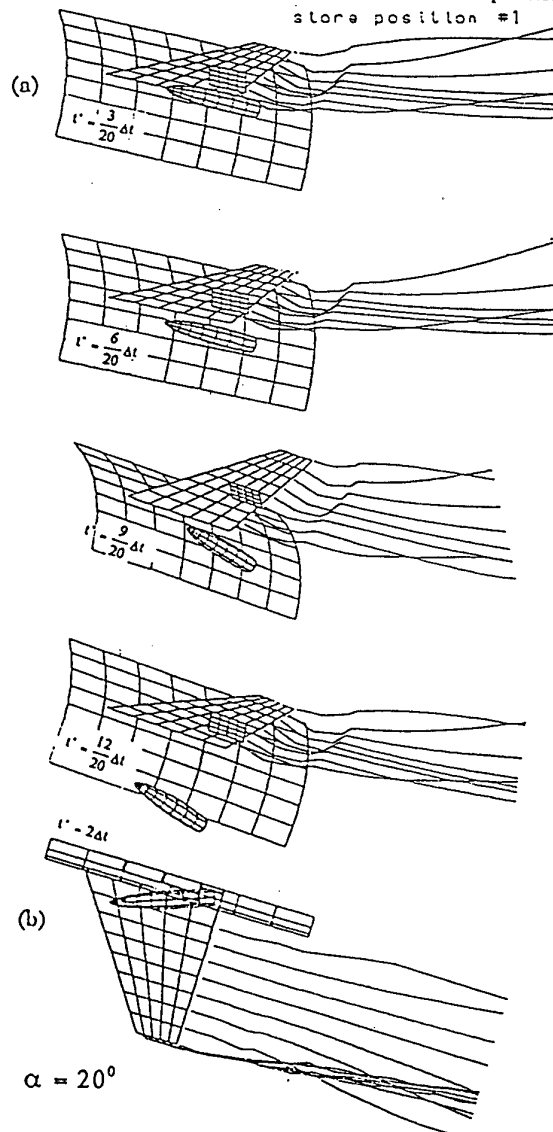


Figure 20. a) Instantaneous store positions at selected times. b) Plan view of the store position at  $t^* = 2 \Delta t$ .

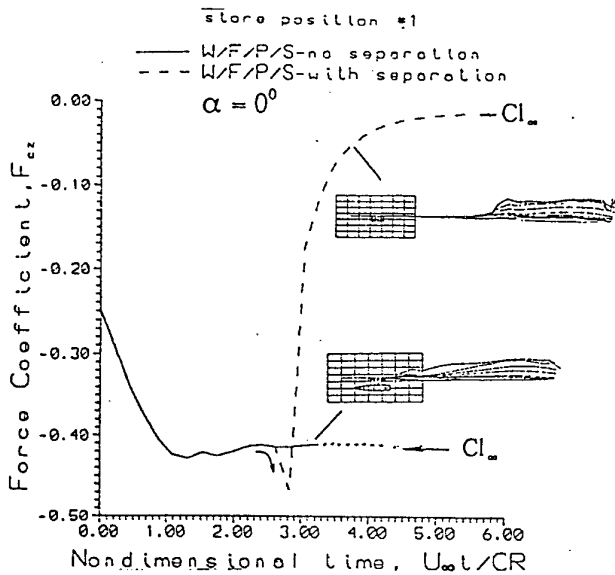


Figure 21. The transient force coefficient,  $F_{\alpha}$ , of the wing before and after the store separation during a constant forward zero angle of attack motion.

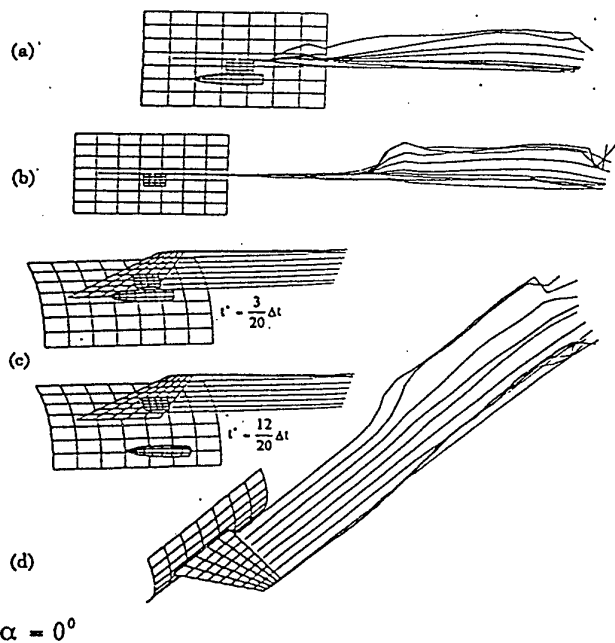


Figure 22. a) Instantaneous wake structures before the store separation. b) Instantaneous wake structures after store separation. c) Store positions. d) Perspective view of the wake showing the pre and post store separation effects.

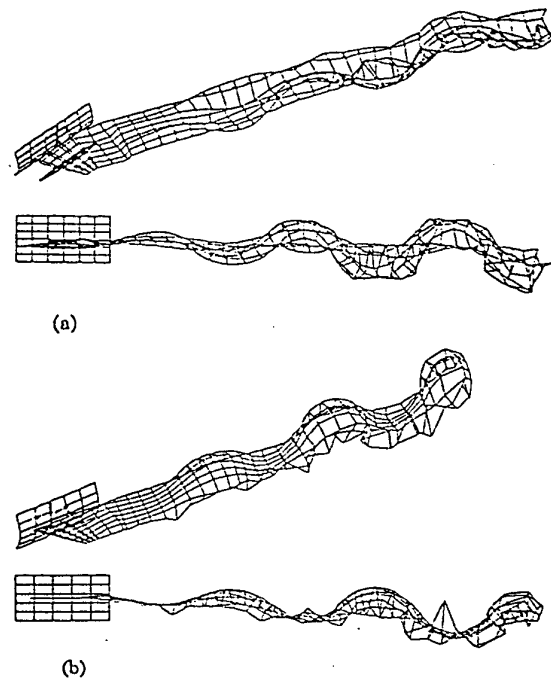


Figure 23. a) Perspective and the side view of the computed vortex wake structure behind the W/F/P/S configuration performing sinusoidal roll motion. b) Perspective and the side view of the computed vortex wake structure behind the W/F/P/S configuration performing sinusoidal pitch motion.

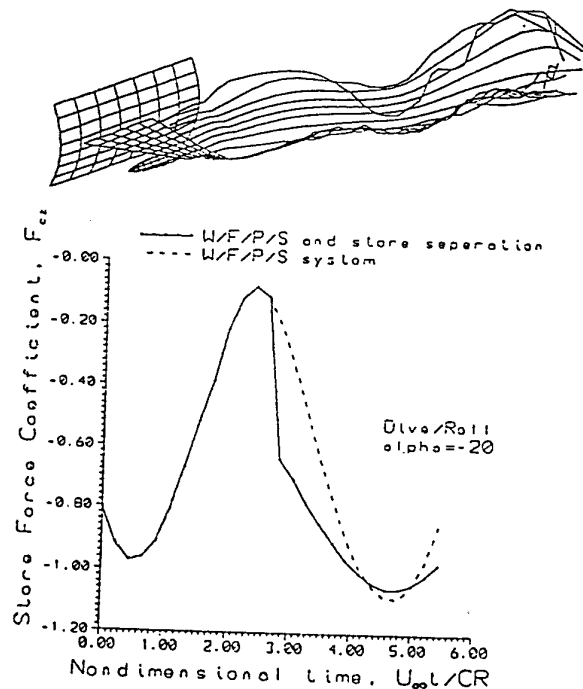


Figure 24. The transient force coefficient,  $F_{\alpha}$ , of the wing before and after store separation during a roll motion with forward dive motion.